

# INTELLIGENT DECISION AIDS FOR HUMAN OPERATORS

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## 1 OVERVIEW

The paper describes the concepts and architectures of intelligent decision aids, which are designed to support human operators in complex mission systems. It starts with a discussion of models for human decision making. These models are used to develop the concepts for intelligent technical devices - like monitoring or diagnosis systems for situation assessment, planning or decision aiding systems for the preparation of actions - which are built to support certain subfunctions in the human decision making process. Several examples of decision aids are presented, which have been developed in the USA, France and Germany. The goal is that the detailed presentation of these projects, together with the discussion of experiences and lessons learned from the implementations shall help potential builders of intelligent decision aids to design similar systems. The areas of application of these decision aids range from air vehicle management and aircraft mission management to air traffic management and command and control systems. The principle of coupling work systems for the modelling of complex and distributed decision making processes is discussed and applied to air traffic management and command and control.

## 2 FUNCTIONAL ANALYSIS OF DECISION MAKING IN MANAGEMENT TASKS

Classical control theory has enabled the engineers to transfer such human operator functions to machines (control systems), which require no explicit handling of knowledge. The advent of symbolic data processing, neural network and artificial intelligence techniques makes it now possible to design automatic systems also for functions which make explicit use of knowledge stored in computers. Such functions are performed, for example, in the cockpit of a military or civilian airplane, at an air traffic controller's work position, at a mission planning work station or in a command and control center.

### 2.1 Basic Functions in Problem Solving

Problem solving can be analysed by considering the general structure of human behavior. The goal-directed interactions of man with the surrounding world can be decomposed into the functional elements of the so-called *recognize-act-cycle* [1,2] (or stimulus-response-cycle):

- MONITORING:** Recognize the actual state of the world and compare it with the desired state (which corresponds to the goal of the interaction).
- DIAGNOSIS:** Analyse the deviations of actual and desired state.
- PLAN GENERATION:** Think about actions to modify the state of the world.
- PLAN SELECTION:** Decide about the necessary actions to reach the desired state.
- PLAN EXECUTION:** Take the necessary actions to change the state of the world.

For many simple tasks a person's physical sensors (eyes, ears, etc.), his brain and his physical effectors (arms, legs, etc.) are sufficient to carry out these functions. This is called "manual interaction". More demanding tasks (e.g. flying a military airplane) go beyond the capabilities of his physical sensor/effector equipment. Therefore, man has invented a great variety of *tools* to support his interactions with the world. The

tools may support ("semi-automatic interaction") or even replace the human functions ("fully automatic").

Generally, knowledge-based human functions are required to solve a problem in the surrounding world. In these cases, the information processing carried out by the human brain in order to find a solution of the problem can be described in a similar way by the following chain of functions:

- Recognition of a problem in connection with the actual state of the world and its representation in a "mental model". Definition of the desired goal state.
- Construction of potential actions (control strategies) to bring the surrounding world from the recognized problem state to desired goal states.
- Selection of criteria to evaluate the different control strategies.
- "Mental simulation" of the effect of the control strategies on the world to assess their efficiency.
- Evaluation of the possible control strategies.
- Selection of the appropriate control strategy to "best" drive the surrounding world to the desired goal state.

### 2.2 Man-Machine Interaction in Work Systems

In the industrial society many of the human interactions with the world happen in so-called *work systems* [3,4,5,6]. The goal of a work system is to fulfill a certain task, for which it has been built. It normally consists of the elements (see Figure 2.2-1): *Operator*, *Work Object* and the *Tool(s)*. The tools are devices or machines which help the operator to fulfill the task. The system elements interact with each other through the operator- and the work-object-interfaces, with the goal to produce a certain output, the *product*.

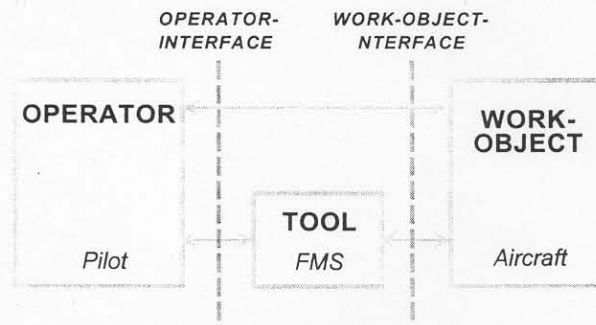


Figure 2.2-1 Declarative Representation of a Work System

The operator can interact with the work-object directly (*manual operation*) or with the help of a tool (*semi-automatic or automatic operation*). The declarative representation which describes the elements making up the work-system in Figure 2.2-1 is instantiated in that Figure with the situation of a pilot in the cockpit of an airplane. Here the operator is the pilot, the work-object is the airplane and the tool is the Flight Management System (FMS) of the aircraft. The goal is to fly the airplane in accordance with the flight plan (or the mission plan in the military case) subject to the ground rules of safe flight and possible directives of Air Traffic Control (Flight Management).

The combination of operator and tool will be called *Man-Machine System* in the following text.

Another (complementary) way of regarding the work-system in Figure 2.2-1 is the procedural (or function-oriented) representation in Figure 2.2-2, which describes those functions performed by the man-machine system which are required in order to reach the goal - a safe flight according to the mission of the aircraft.

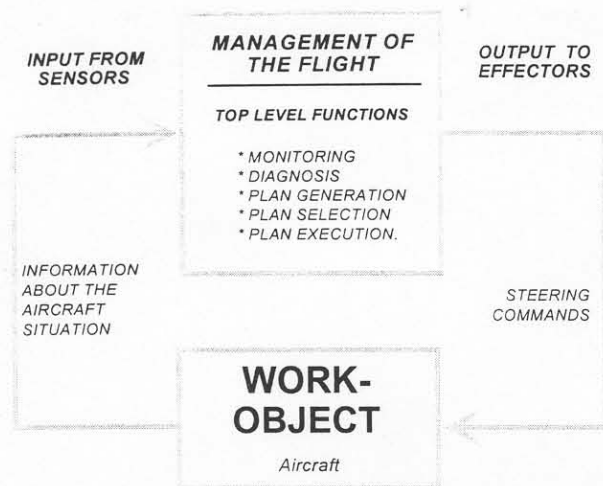


Figure 2.2-2 Procedural Representation of a Work System

One can describe the top level functions also in this case as

- Monitoring
- Diagnosis
- Plan generation
- Plan selection
- Plan execution.

In manual flight, the pilot transforms the aircraft state into its desired value, feeding the output of the work-process (the control commands) to the effectors (the actuators of the airplane). In the case of a semi-automatic or automatic flight, tools (like the Flight Management System) contribute to performing (partially or totally) the top level functions.

It will be shown in chapter 4 that complex aerospace systems (e.g. air traffic management systems or command and control centers) can be represented as networks of coupled work systems.

### 2.3 Functional Architecture of Management Functions

The examples discussed in this paper are related to the *management* of aerospace systems. Based on the results of a former AGARD Working Group [7], the general structure of such management functions can be described as shown in the Figure 2.3-1.

The functional elements of the management function are arranged in a certain *functional architecture*, and they have been grouped together in the more general functions

- situation assessment
- plan generation
- plan implementation, and
- coordination.

The *coordination* function in this architecture controls the execution of the other individual functional elements, and coordinates the total management function with other work systems.

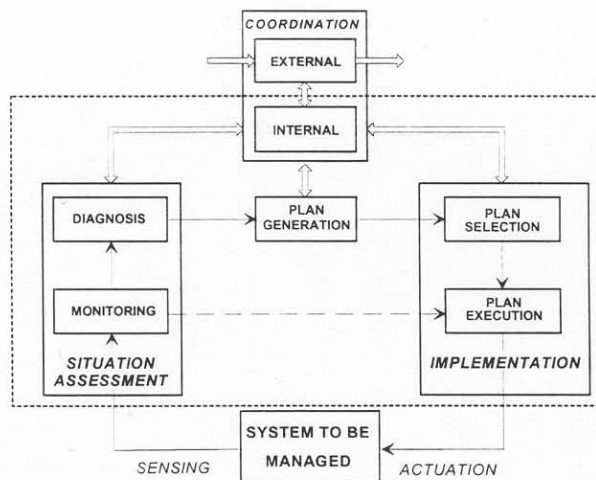


Figure 2.3-1 Structure of Management Functions

## 3 EXAMPLES OF DECISION AIDS FOR AIRCRAFT PILOTS AND AIR TRAFFIC CONTROLLERS

### 3.1 Approach Procedures Expert System (APES)

#### 3.1.1 Introduction

The approach and landing phase of flight is considered to be one of the most workload intensive of all the phases of flight. In fact, recent studies have shown that 25-50% of civilian aircraft accidents occur during this phase [8]. A major factor contributing to these incidents is the extensive cognitive demand placed upon the pilot [9]. The pilot must recall and apply specific instrument flight rules, remember correct task sequences, and calculate timings, while simultaneously controlling the aircraft and monitoring its performance. In addition, the pilot must integrate information from multiple sources and replan according to air traffic control's (ATC's) redirection. Because of the extensive cognitive load, number of procedures, and „rules of thumb“ associated with the instrument approach, the instrument approach domain is well-suited for a decision aid application.

#### 3.1.2 Objectives

The goal of this study was to assess the usefulness and performance of a prototype decision aid, Approach Procedures Expert System (APES), for flying instrument approaches by evaluating it in a pilot-in-the-loop simulation. Because the decision aid is inseparable from its interface, both the decision aid and the pilot-vehicle interface (PVI) were evaluated; however, the emphasis of the study was placed on the value of the decision aid advice. The objectives of the study were to:

- (1) Assess the *effectiveness* of APES for supporting approach tasks and its potential for reducing pilot workload, increasing situational awareness, and improving performance.
- (2) Assess the *performance* of the decision aid to determine if APES advice was accurate and timely enough to assist the pilot in flying instrument approaches.
- (3) Assess the *understandability* and *usability* of the pilot-vehicle interface to determine if the interface allowed the pilot to easily interpret and use APES advice.

#### 3.1.3 Approach Procedures Expert System (APES)

The intent of the APES prototype is to reduce pilot workload, increase situational awareness, and improve performance and

safety. The APES simultaneously monitors aircraft performance, informs the pilot of appropriate corrective actions when deviations occur, and provides procedural advice according to the phase of the approach (i.e., holding, initial approach, final approach, missed approach). To accomplish this, the APES functions in two assistant roles: as an „advisory copilot“ and as an „advisory pilot.“ As an „advisory copilot“ the decision aid advises and prompts the pilot as a copilot would in a crew environment, such as advising when the aircraft deviated from assigned parameters (e.g., altitude, airspeed, etc.). As an „advisory pilot“ the decision aid provides guidance relevant to the instrument flight rules (IFRs) needed for the specific phases of the approach.

Audio, a natural form of communication that would exist between the pilot and copilot, is the primary pilot-vehicle interface for the APES. Visual messages are employed for redundancy and when it would be impractical to use audio. The following sections describe the developmental process, the APES system architecture, and the Pilot-Vehicle Interface (PVI).

### 3.1.3.1 Overview of the APES Developmental Process

The first step in the development of the APES was capturing the expertise of experienced pilots through a knowledge acquisition process. A knowledge engineer conducted an iterative interview process with several subject matter experts (experienced in-house pilots). This process identified the precise steps that were necessary for flying the various phases of an approach. The knowledge engineer then modeled the actions recommended by the expert pilots and created process flow diagrams. The process flow diagrams served as a basis for the APES algorithm.

The APES prototype was then integrated into a simulator and tested in an iterative check-out process. Test approaches were flown with various flying patterns to exercise all of APES decision points and to determine if APES was functioning as intended. Design flaws were identified and corrected. Upon completion of the check-out process, a verification test was conducted. An in-house pilot, unfamiliar with the APES, flew all of the approaches that were used in the study. Design deficiencies, that went undetected during the iterative design process, were identified and corrected. APES was then formally evaluated in the current study.

### 3.1.3.2 APES Architecture

The APES prototype system consists of the following basic components. (The interaction of these components is depicted in Figure 3.1-1.)

- (1) a dynamic aircraft status file
- (2) a set of facts representing aircraft-specific and approach-specific databases
- (3) a set of rules where the expert knowledge resides
- (4) a forward-chaining inference engine which takes advantage of the speed of the „Rete“ algorithm to provide faster performance

### APES Inputs

As depicted in Figure 3.1-1, input to the APES comes from three sources: current aircraft flight parameters, a database of aircraft specific facts, and a database of approach specific facts. Examples of the types of input that are used by APES include the following:

- Aircraft Status Data
  - Current Altitude / Heading / Airspeed
  - Current Navigation Aid Radial
  - Current Navigational Radio Channel
- Aircraft Specific Facts
  - Holding Airspeed
  - Fuel Weight
  - Approach Airspeed

- Approach Specific Facts
  - Holding Altitude
  - Final Approach Course.

An aircraft specific input file was created for each aircraft type in order to allow a generic APES to be embedded in aircraft (or aircraft simulators) of different types. Data for the aircraft are loaded from the corresponding aircraft specific data file during program initialization. For purposes of this study, the aircraft specific facts were limited to an F-16 aircraft. Also the approach specific facts were limited to eight approach plates; however, the APES can accommodate an unlimited number of approach plates.

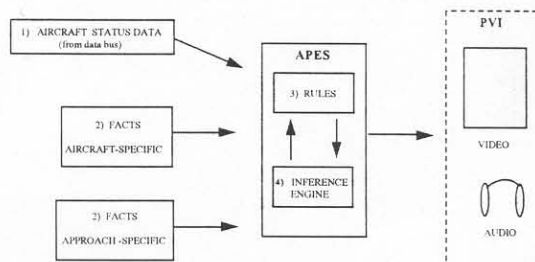


Figure 3.1-1 APES System Architecture

### APES Implementation

The expert systems development tool used for this study was the C Language Integrated Production System (CLIPS) developed at the NASA Johnson Space Center [10,11]. CLIPS is a distinguished member of the OPS-5 family of expert systems shells, and has been extensively used in many applications, including a variety of NASA missions. The CLIPS inference engine uses the highly efficient Rete algorithm, which contributes to CLIPS' excellent run-time characteristics. CLIPS avoids the timing problems associated with slower running expert systems because the Rete algorithm does not reconsider a rule (that has already been executed) for activation until a subsequent change in the value of one or more of its antecedents has occurred.

### 3.1.3.3 APES Pilot-Vehicle Interface

The primary pilot interface for the APES is voice message presentation. For example, if the pilot deviates more than +/- 2 degrees from course, the APES „advisory copilot“ component would compute a heading to re-intercept the course and announce „Turn/Come Right/Left Heading XXX.“ Once reestablished on the course, APES would then announce „Maintain (course) XXX.“ To output a voice message, the APES passes a text string to the voice module of the Silicon Graphics host system. The Silicon Graphics system then generates the voice message by combining words that are listed in a vocabulary database of approximately 50 words.

APES voice messages are reinforced with the visual presentation of text information. The APES continually displays updated target values for radio channel/frequency, altitude, airspeed, heading, and course in a scratchpad area to allow the pilot to manipulate appropriate command marker and course indicator settings. APES also displays current (target) values for radio, altitude, airspeed, heading and course on a dedicated Cathode Ray Tube (CRT). This CRT is also used to display more complex textual information, such as pre-approach and final approach checklists. The cockpit displays are depicted in Figure 3.1-2.

### 3.1.4 Methodology

To accomplish the test objectives, 16 pilots flew a series of instrument approaches in the cockpit simulator. The presence of the decision aid, the orientation of the electronic approach plate

One way to mitigate the possible effects of reduced situational awareness and system confidence is through proper training of the decision aid logic. This training would enable the pilot to develop an accurate mental model of the reasoning behind the advice [12]. Equally important is proper design of the pilot-vehicle interface to facilitate the human-computer interaction and allow the pilot to easily interpret the decision aid advice. An effective decision aid may also need to include user-selectable options as part of its design, giving the pilot flexibility in configuring the PVI. For example, the pilot may find it useful to configure display modes (audio or visual) for certain types of advice (e.g., altitude, airspeed, course). The pilot may also find it beneficial to set the priority levels (e.g., primary and secondary) of the various advice types, as well as, adjust their tolerance windows (e.g., +/- 100 feet for altitude deviation).

## 3.2 Copilote Electronique

### 3.2.1 Introduction

Since 1994, the Technical Service for Aeronautical Telecommunication and Equipment of French DGA (STTE) launched an exploratory development program concerning a high level decision aid, using Knowledge-Based System (KBS) technology for an advanced combat Aircraft. This french project for an in flight mission planning Decision Aid is called "Copilote Electronique" [13]. The exploratory development program is lead by Dassault Aviation with the support of many industrial and scientific partners (SAGEM, Dassault Electronique, Matra Défense, Sextant Avionique, IMASSA, ONERA...). It aims at introducing, this kind of decision aid within a 2010 horizon for a future Rafale standard (The Rafale aircraft will enter the French Air Forces at the start of the next century).

### 3.2.2 Operational Objectives

- *The operational objectives of the Copilote Electronique are surveyed in order to precise the domains of assistance that are relevant for such a system.*

Before the launch of the Exploratory Development an action was initiated by DRET the french military research agency to survey the need for pilot assistance in french airforce programs and the feasibility of KBS as a potential technical answer. The need was expressed by senior pilots of the french airforce and navy, with experience of Mirage F1, Mirage 2000 and Super Etendard. The cognitive analysis of pilots activities was conducted by CERMA (Centre for Medical studies and research in Aerospace).

Within the context of the Copilote Electronique program this initial survey was completed and reviewed in front of the forecasted definition of the Rafale missions and system standards. This involved a specialist of the Rafale program from the CEAM (French air force test center) as well as Dassault test pilots currently involved in the definition of the new program.

This section do not address specific requirements linked with the Rafale program but the generic needs of an on-board mission planning activity in a future combat aircraft.

Conducting penetration missions in hostile territory has always raised problems of workload on single pilot. Regardless of aircraft configuration and avionics the planning activity is a very difficult task for the pilot in flight. This includes route selection, ECM employment (like activating and shutting down jammers, throwing decoys...), flight monitoring (following profile, respecting timing, handling communication with C3I...), attack planning and weapon selection... This overload problem has generally been solved by applying strict mission control rules over a very detailed ground-based mission preparation.

It is recognised for example that in a typical Penetration Mission at low altitude and high speed within enemy territory, a pilot is following a strict time schedule with little possibilities to divert from it. For instance at an altitude of 300 to 500 feet and a speed of 500 knots only a few seconds of delay over the way points can be accepted. If such timing is not followed coordination between friendly ressources is in danger, the efficiency of weapon delivery is lowered and possibly, the firing of the aircraft by friendly ground defense will happen when crossing back the Front Edge of Battle Area (FEBA). **Figure 3.2-1.**

The extreme time pressure imposed on pilots of combat aircraft makes the planning activity very complex and dynamic. With such an extreme time pressure, in-flight planning could be considered as totally unrealistic, but it must be recognized that most of the time real missions will be disturbed by unexpected events. This leaves no choice to the pilot who needs replanning. Many of those unexpected events have been listed in the domain of aircraft ressources. One may mention engine failures, jammed positioning systems, sensor default... They are also numerous and frequent in the tactical domain. For instance one will

encounter hostile Conter Air Patrol aircraft (CAP), unknown ground missile sites (SAM), electronic counter measures... There are of course perturbations due to the natural mission conditions such as weather evolutions, unregistered ground obstacles... Finally one have to mention coordination problems between raid and escort patrol or Command and Control aircraft (AWACS) as well as possible human errors.

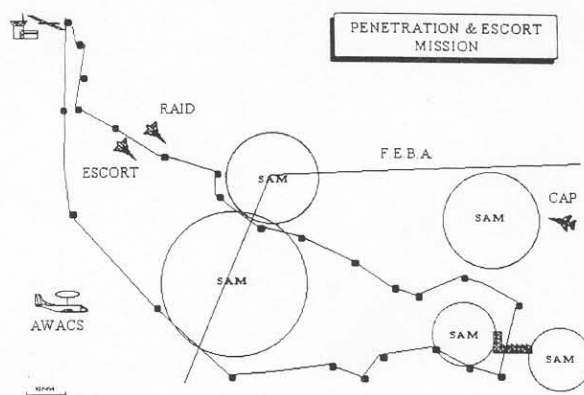


Figure 3.2-1 Penetration and Escort Mission

Therefore a strictly nominal execution of a mission plan prepared on ground is very unlikely to happen according to the experience of Mirage F1 CR or Mirage 2000 operations as well as Rafale extrapolations. Even simulation campains will show frequent perturbations with the necessity for the pilot to react by in flight mission planning. A recent Rafale simulated test of a sweep mission exemplified the interest of some pilot support in heavy workload situation.

In such cases the functional requirements of pilot planning task ranges from flying activities, navigation, ressources management, information pick up, to tactical response elaboration.

For instance an Air to Air Engagement during an escort mission was analysed in detail. In case of ennemy engagement, a pilot has to planify an adapted behavior to analyse the tactical situation including platform manoeuver and sensor control. He needs to coordinate the friendly actions through communication with the penetrating raid bomber leader and with its fighter wingman. He exchanges tactical information, selects tactics, assigns target and he instantiates a proper offensive plan including weapon preparation, launch point calculations, flight path trajectories generation, evaluation of kill and survival predictions...

In conclusion of this section it can be assessed that a requirement for in flight mission planning is perceived in future low altitude high speed penetration missions and air to air escort missions (this is not to say that in flight planning is not needed on other missions such as air to air interception at high altitude but this analysis was not carried exhaustively within the scope of the project).

The planning task not only concerns navigation strategies but also tactical offensive and defensive management as well as aircraft ressources monitoring. These many planning concerns overlaps during active mission phases such as air to air engagement. Consequences of bad planification as taking wrong decisions, acting too late, or executing improperly the plan, are generally intolerable. It may result in a crash, or an unsuccessful mission, or the loss of aircraft and pilot ...

A single pilot with current avionics is unlikely to perform such in flight planning complex task without errors. A need for assistance is perceived, leading to increased autommation as well as planning support. It was noticed during the analysis phase of the Copilote Electronique that there is a general preference for systems providing assistance in tasks such as calculating fuel, plotting routes, identifying risks... Pilots really

care for better situation assessment in the planning process. This was well expressed by Major G.W. Breeschoten in his keynote address of Guidance and Control Panel 53rd Symposium [14]:

"I do not want the system to think for me, at least in the sense that it prescribes my tactical actions. It can to some extent think with me."

Nevertheless, as critical decisions are to be taken on uncertain or tactical aspects of mission, aircraft designers often rely on pilots judgement. This tendency is even currently required by Air Forces.

As a result of this requirement analysis the Copilote Electronique project is oriented toward a multi-agent (or multi-assistance) organisation that best express the human reasoning in the guidance and control domain. For the development phase of the program it was then decided to consider the expert domains that pilots distinguish in the conduct of penetration and escort mission.

These domains are:

- **Aircraft system management** (« domaine Avion »), including:
  - System evaluation
    - Monitoring discrete events and continuous signals.
    - Assessing real avionic systems states and dependability.
  - System planning
    - Planning the avionic systems reconfiguration.
    - Scheduling of action & ressources according to the plan.
- **Tactical management** (« domaine Tactique Sol » & « domaine Tactique Air »), including:
  - Tactical assessment
    - Analysis of friendly & foe forces.
    - Elaboration of forecasted evolutions.
    - Assessment of risk/efficiency according to present plan.
  - Tactical planning
    - Planning tactics according to the threats and pilot strategies.
    - Scheduling actions and ressources according to the tactics.
    - Handling conflicts among proposed tactics.
- **Mission management** (« domaine Mission »), including:
  - Mission condition assessment.
    - Mapping of pre-mission meteorological briefing onto possible routes.
    - Mapping of pre-mission geographical data onto possible routes.
  - Route planning
    - Selecting re-routing options according to the updated mission context.
    - Planning new routes.
    - Monitoring possible routes with quality estimates.
- **Man-machine coordination** (« domaine Coherence des assistances »), including:
  - Pilot behavior assessment.
    - Mapping pre-mission strategic option to in-flight planning.
    - Inferring pilot intent from observed actions.
  - Planning management
    - Driving experts planning efforts toward a common goal in accordance with pilot strategy
    - Insuring proposed plan quality
  - Dialogue management.
    - Presenting relevant informations to the pilot
    - Handling pilot queries.

### 3.2.3 Ergonomical Design

- *The advantages of a cognitive assistant approach over an automatic planning approach and the ergonomical rules settled by the project to facilitate in flight Pilot <-> System relationship are presented showing the "Copilote Electronique" orientations in that respect.*

To design the proper decision aid it is necessary to analyse the level of autonomy best adapted to the in flight planning process. In front of the increasing complexity of avionic systems and weapon systems it is certainly desirable to design systems capable of taking responsibility of lots of pilot decision activities. The present technological push, best exemplified by the well known knowledge-based systems, expert systems, constraint programming tools, neural nets... leaves an open field to the dream of full automation. Of course some caution should be taken in terms of feasibility for these techniques in real time avionics. As Wiener and Curry showed [15], full automation can have serious drawbacks with a risk in the long term of having operators unable to conduct the missions.

Various embedded functions, such as navigation, piloting, aircraft status management, weapons system management, and in some extension sensors management have been successfully automated by classical software engineering methods, but the addition of such separate and independent automated functions is more and more difficult to control in real time situations by human pilots.

Automated functions are intended to increase in number and complexity, in the foreseen tactical context of year 2010. Such context is characterised by a great number of various possible threats, with electronic war systems and new sophisticated weapons. Operational experts think that future pilots will have some difficulties with this combinatory explosion of information sources unless being assisted in their reasoning tasks.

Within the "Copilote Electronique" project the tasks were cautiously analysed in terms of potential for automation and/or assistance. The first work was based on the guidelines of the AGARD advisory report on improved guidance and Control for the automation at the Man-Machine Interface [16].

These guidelines expressed that tasks requiring highly accurate responses, fastidious and repetitive actions, and exhaustive calculations are good candidate to automation. On the other hand, tasks requiring judgement, multi-sensory information gathering, hypothetical reasoning, contingency reaction... are best suited for a "Man in the loop" design.

Planning tasks are certainly of the second type. Those tasks like system reconfiguration, ressources scheduling, navigation, fuel monitoring threat analysis, threat avoidance, threat engagement, command control and communication, sensor control and weapon management were structured according to the expert domains:

- System management
- Tactics management (air-air and air-ground)
- Mission management

In the System area, planning is more often an optimization of fine grain plan in front of the flight parameters evolution and generalised state of the navigation and weapon systems (including faulty states).

In the Tactics area, planning is reactive. Threats are popping up as unexpected event and disrupt from the planned behavior established on ground during the preparation phase.

In the Mission area, the result of the mission preparation remains the guide for all in flight planning. The task here consists of adaptations of the nominal plan, plan refinement in a precise context, choice of alternative plans...

At this stage of the design the approach was oriented toward a human centered design. This was based on human factors evidences from the aviation history, which are addressed in the "Copilote Electronique" team by IMASSA/CERMA [17].

This study resulted in "user oriented rules" that has to be used in the design of the Copilote Electronique

Those rules can be summarised as follows:

- (1) pilot anticipates and needs anticipation assistance on contrary of "classical engineer designed" assistance which are often too reactive,
- (2) pilot's decisions reflect often compromises between mental load and ideal response to the situation, so pure optimality is not to be researched if pilot has no sufficient time to understand,
- (3) following their own personal skills, different pilots may organise work differently, assistance must be adapted to these skills,
- (4) assistance must be homogeneous, and it will be preferable to rely on specialised expert for each operational domain (e.g. Strike or Air Defense expertise) so resulting assistance will produce constant understanding interpretation model that will avoid surprises for pilot,
- (5) assistance must know and respect its own limits,
- (6) system design may use "what if" approach to be less reactive,
- (7) dialogue must be adapted to context, pilot intents and pilot load,
- (8) dialogue must be space oriented and interactive, better use vocal media than written, but avoid saturation,
- (9) respect logic of pilot understanding, that means rely on the understanding model designed with expert pilots.

The french Copilote Electronique project is oriented toward a cognitive assistance as a consequence of this ergonomical analysis.

### 3.2.4 Functional Architecture

- The organic architecture established for the "Copilote Electronique and the proper mechanisms supporting the cognitive assistant approach of mission planning are described.

In order to achieve the main objective of demonstrating the concept of a cognitive assistance for future combat aircraft it is necessary to organise the selected expert domains that will perform the required functionalities of in flight decision aid.

The Copilote Electronique project finalized such an architecture by the end of 1994. Figure 3.2-2.

The top level organization of the expert domains in the Copilote Electronique is in accordance with the Functional Decomposition of Generic decision system in Guidance and Control as proposed by AGARD Working Group 11 [18].

The two main activities of situation assessment and planning are represented in each of the expert domains. All the expert domains are communicating with others to enrich their vision of the situation and to elaborate plans. The coordination activity is taken in charge by a specific expert supervising the others.

An expert domain, absorbs high rates of raw information, select and highlight the more crucial ones, before initiating dialogue with the other experts. Raw data is provided by the existing technical functions of the Navigation and weapon system assuming that a data sharing mechanism is available (it is the case with Rafale and M2000 type of system).

The planning reasoning layer of each domain take entries from the assessment level. Expert description of the situation are not propagated to each domain but relevant informations can be accessed on request. Planning directives are passed by the supervising expert to the concerned specialists according to the problems encountered. Such directives includes, problem scope, constraints, and pilot strategies. The experts reason in a manner adapted to current situation and mental load of the pilot. They consider a restricted set of actions choice for the pilot and examine all consequences before proposing them.

Dialog with the Pilot is handled at the supervision expert level. It insures that a single coherent proposal will be presented by the group of expert domains. It also minimize the informational workload of the pilot and handles the pilot queries through the use of « regular » man-machine interface of the Rafale aircraft.

The external world perception, the communication with other agents and the plan execution are not part of the Copilote Electronique responsibility but it can be assumed that these activities are present in the current Navigation and Weapon system (SNA) in which the Copilote Electronique is integrated.

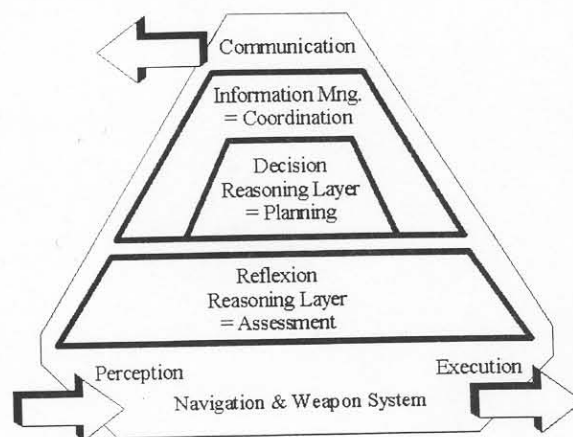


Figure 3.2-2 Functional Architecture of the Copilote Electronique

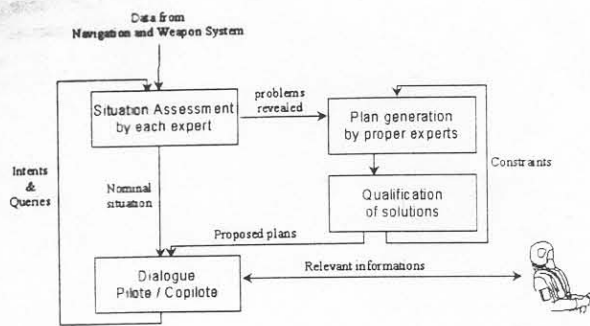
The dynamic behavior of the Copilote Electronique is driven by a cyclic assessment of the situation by the expert domains (the period of the cycle differing from one expert to another) and an event driven planning activity based on the warnings issued by the assessment layer. The planning activity includes several steps of generation driven by the experts best suited to the revealed problem and the pilot strategy. Those steps are followed by qualification treatment. Qualification is performed by all the expert domains so that the quality of the proposed solution is seen globally and not only by a single domain with possible conflicts with other fields. In case of insufficient quality constraints are posted by the expert domain to help the other in refining their proposal. Once finished the planning activity gives results to the dialog manager. Plans are joined to situational information to be presented to the pilot. Two levels of dialog are handled (rich or succinct) in order to adapt the information flow to the pilot workload.

The Figure 3.2-3 present this process.

### 3.2.5 Development Status

- A short overview of the knowledge-based development process engaged is given

The goal of the functional development, launched in 1994 for a three years duration, is a ground simulation, without real time constraints, to illustrate the potential of the "Copilote Electronique" in situation of strike and escort missions, with low altitude penetration constraints. The software architecture at this stage is resolutely a cooperative set of expert modules mapping the expert domains [19]. To conduct this development Dassault Aviation set up a consortium based on the french industrial competences.



**Figure 3.2-3 Block Diagram of the Copilote Electronique Functions**

Responsibilities within the consortium are:

- Ergonomics rules and knowledge acquisition methods and verification tasks  
-> IMASSA/CERMA  
System Status Assessment and Management  
-> SAGEM
- Tactical Situation Assessment and Management (Ground threat and defensive Counter Measures)  
-> DASSAULT ELECTRONIQUE
- Tactical Situation Assessment and Management (Air threat and offensive Weapons)  
-> MATRA DEFENSE
- Mission Conditions Assessment and Mission Management  
-> SEXTANT AVIONIQUE
- Pilot Assessment, action plans assessment, relevant information management and man-machine interface  
-> DASSAULT AVIATION

Knowledge engineering techniques are for expertise initial design. With IMASSA, a specific method for eliciting and formalising pilot's expert knowledge was studied and is used. It is supported by a formalisation tool called X-PERT. It is confirmed by present campaigns that pilot expertise can be collected coherently in all the expert domains and that generic behaviors (not linked with a specific Navigation and weapon system) can be used in the expert modules. Generic expertise has to be supplemented by extensive knowledge evaluation and correction in simulator, in order to represent specific behaviors linked with the new system like Rafale. The main issue for the future design is to accept expertise from pilot during operational life of the system.

The technical specification is driven toward a flexible heterogeneous implementation paradigm. The Copilote Electronique expert modules are organised in a multi-agent system using Distributed Artificial Intelligence techniques [20]. Another very important technical issue is the definition of a common "plans and goals" exchange language between all specific assistance modules, and great efforts are made to maintain this common message glossary. Within the functional development Dassault Aviation proposed an exchange language called LDI which provides a CORBA like facility for object communication.

A unifying technical principle is adopted to facilitate the architecture design via the **intent planning paradigm**. This principle is essential to fulfil general ergonomics constraints: assistance must not participate to the signalled existing overloading factors. Intent recognition is a challenging but promising direction and can be made easier by extended preparation mission plans and procedures (for each pilot activity) that will be perhaps the new "automated and personalised" check lists version of the future [21].

At present, a mock-up is implemented. It uses a set of unix workstations (one for each expert domain) linked to a Rafale simulator with « engineer » type of interface. The mock-up shows non real time behavior of the expert modules integrated in a complete Copilote Electronique system. A synthesis of the presented functionalities will be realised in spring 1997.

### 3.2.6 Conclusions

This example opens to the possible future developments of intelligent decision aids for in flight mission planning within future combat aircraft.

The technology is available today to provide viable knowledge system solutions to well-chosen and well-defined problems. It can be expected to see more and more successful projects on such on-board applications, as both the research, the technology and engineering skills of application developers improve.

But this process may be slower than was thought. Main reason is that knowledge acquisition tasks and user oriented ergonomics rules compliance must be integrated in the overall engineering cycle.

The french Copilote Electronique project has been carefully planned considering those methodological difficulties.

After a long design phase the Copilote Electronique is now in a software development phase. The planning domains are the main drivers of this development. They are developed by french industrial partners in a federative approach. Each partner brings to the project a specific background, with a high value knowledge of his planning field and mastering of appropriate planning mechanisms. This results in a very rich but heterogeneous multi-expert, multi-industrial planning system.

The Copilote Electronique, not only reach a successful behavior in each planning field, but also achieves a coherent assistance for in flight decision aid. Special care is taken to analyse interdependancies between the various plans and to respect the rules of a good man-machine relationship. Expert pilots give feedback on the quality and acceptability of the resulting planning assistant. According to their remarks the architecture, mechanisms and knowledge of the Copilote Electronique planners can be tuned. Present scenarios give confidence on the resulting operational benefits of the assistance system.

Planning proposals will be demonstrated on a realistic full mission simulator after optimisation of the present mock-up. Real time performances of the resulting planning system will be optimised with the help of current technological progress (specially modular avionics and new software environment). It is believed that the key of a successful in flight planning is more in the pilots cognitive abilities than in hardware/software evolution.

The first steps of the Exploratory Development phase confirms that the distributed architecture and the Human driven design approach are good drivers for success.

## 3.3 Cockpit Assistant System (CASSY) and Crew Assistant Military Aircraft (CAMA)

### 3.3.1 Introduction

The central idea for the development of CASSY and CAMA is, to ensure that the crew will have all necessary and useful information without overloading, according to human-centered automation [22]. Design criteria were established, which aim at a cooperative function distribution between man and machine like that of two partners [23].

Both man and machine are active in parallel by assessing the situation and looking for conflict solutions at the same time. In contrast with current man-machine interaction, both assist each other while heading for the same goals. Consequently [22, Page 84] demands: „Each element of the system must have knowledge of the others' intent. Cross monitoring (of machine by human, of human by machine and ultimately of human by human) can only be effective if the agent monitoring

understands what the monitored agent is trying to accomplish, and in some cases, why." Hence, the level of understanding what each element of the system is doing should be as high as possible.

Derived from the demands on automation a knowledge-based aiding system should comply with two basic requirements [24,25]:

- Requirement (1): As part of the presentation of entire flight situation the system must ensure to guide the attention of the cockpit crew towards the objective most urgent task or sub-task.
- Requirement (2): If requirement (1) is met, and if there (still) occurs a situation of over-demanding cockpit crew resources, the situation has to be transformed - by use of technical means - into a situation which can be handled normally by the cockpit crew.

Basic requirement (1) is to ensure situation awareness of the crew. In part, it can be transferred into the functional requirement for the assistant system of being capable to assess the situation on its own.

Pilot's workload has become a critical issue as the mission complexity has grown. It is particularly desirable to reduce the need to compose the relevant information from numerous separately displayed data. The ability of the assistant system to detect conflicts, to initiate and to carry out its own conflict-solving process and to recommend and explain this solution to the pilot, gives the pilot sufficient time to cope with unanticipated events and to act reasonably (requirement 2.). This appears to be a flexible situation-dependent, and cooperative share in situation assessment and conflict resolution between the electronic and the human crew member. Automation, like recommended in the past, seemed to be very attractive. However, it has to be handled with care not to find the pilot out of the loop of conducting the mission and flying the airplane (check „automate“ and come back in „manual“ if necessary).

Ignoring the basic requirements, automation changes the pilot's task into automation management, merely monitoring automatic systems. Increasing workload of the crew should lead to machine initiatives for anticipating of future mission and conflict solving recommendations [25].

### 3.3.2 Functional Layout of Knowledge-Based Assistant Systems

If the above mentioned design-criteria and requirements are perfectly fulfilled, this will result in an electronic crew member which is capable:

- to understand the abstract goals of a mission,
- to assess mission, environment and system information the crew needs,
- to detect the pilot's intent and possible errors as part of situation analysis,
- to support during planning and decision making by recommendations of the conflict solver and
- to know, how to present it to the crew effectively by the dialogue manager

and the following functional layout (Figure 3.3-1) of an electronic crew member as a Knowledge-based Assistant Systems is to be made:

The functional module of **Situation analysis** deals with the ability to comprehensively understand a current situation. This process starts with the perception of the situational features. The machine infers from these features abstract objects of the situation. This closely resembles the human way of situation analysis. The process ends with an overall situation description, also covering weather reports, threat locations and aircraft state as well as elements like evaluated mission-goals, plans, present and future tasks, actions and deviations from estimated behavior. On the basis of the situation description the situation diagnosis process recognizes and predicts conflicts from

observable indicators, caused by events in the domain of either aircraft, pilot or environment.

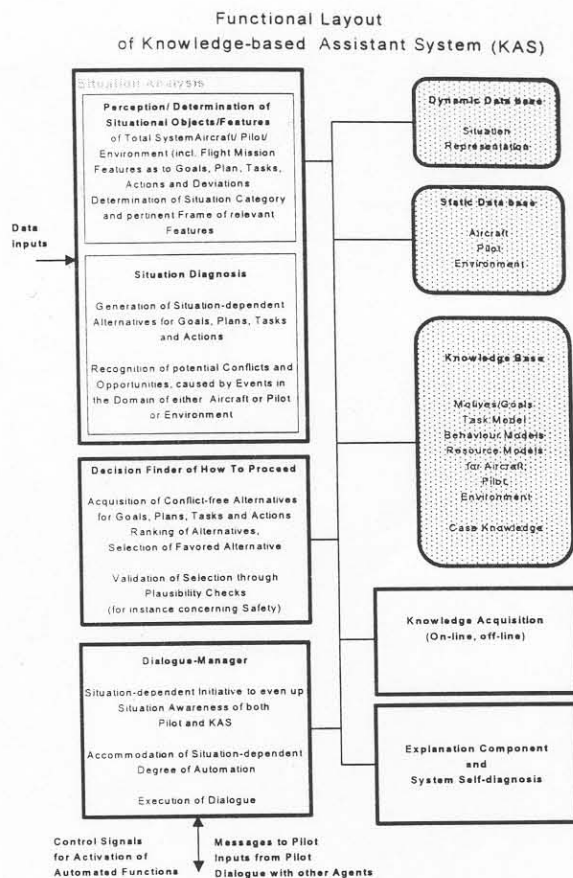


Figure 3.3-1 Generic structure a knowledge-based assistant system

Alternatives for goals, plans, tasks and actions are generated including that one, which represents the given flight plan, and all are checked with respect to potential harmful conflicts. If conflicts are detected, only the conflict-free alternatives are passed onto the conflict solver. The **conflict solving** is ranking these alternatives and selects the most favored alternative on the basis of the mission success criteria.

**Dialogue management** insures effective communication with the crew. This functional component as the front-end of an assistant system is to present all necessary and useful information in a way, that it is easy to comprehend. Messages to the cockpit crew should be tuned and tailored to the current situation especially with respect to the resources of the crew. Pilot-inputs to the system should allow initialization of services and decision support without tedious or distracting input actions.

**Knowledge** processing needs a dynamic object-orientated **representation** of the situation-describing objects. The representation covers sensor data as well as very abstract objects like the whole flight plan or, for instance, the recognized intent of the crew.

Other knowledge bases are essential to express and enable access to domain knowledge and to permit inference. Models about motives and goals, task selection, execution knowledge and demand for resources as well as behavior models are important examples of this kind of knowledge, executed by additional information about the crew member.

Static data bases for navigation purposes or threat data bases can already be considered as standard.

The expert knowledge embodied in the system has to be obtained in a systematic way. **Knowledge acquisition** appears as the bottle neck during development of the knowledge-based assistant system. Well-defined and efficient algorithms and methods have to be used to map the real world with its disguised structure and uncertainties.

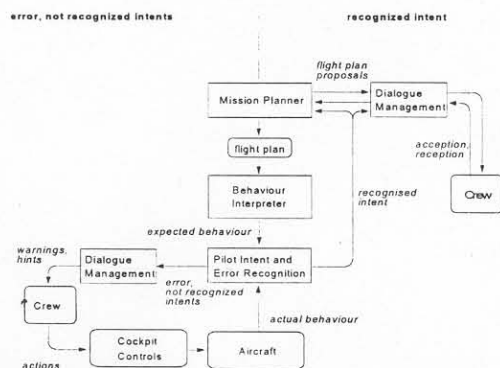
In order to increase user acceptance, it is desirable that the system contains a justification or **explaining component**. First of all the user should be conscious of the rules that are applied in the algorithm to obtain a solution or system state to gain confidence to the system.

**System self-diagnosis** makes sure that the hints and services to the crew will be really useful. The system must be able to realize, if information concerning the actual situation might be insufficient to assist the crew, or that the system itself is not working all right and needs to be corrected.

### 3.3.3 Monitoring of Pilot Behaviour

As pointed out, a vital prerequisite for the machine system's capability to provide assistance in all situations is the ability of correct and comprehensive situation assessment. This means, the system must be aware not only of the aircraft and its environment but also of the crew's aims, tasks and resources. In this case the system will be able to predict information and assistance needs of the pilot crew and to organise its task support.

The machine's situation assessment process can be realized by monitoring and interpretation of the pilot actions within two loops. (Figure 3.3-2).



**Figure 3.3-2 Monitoring and Interpretation of Pilot Behaviour**

The first loop starts with the generation of expected pilot actions by use of knowledge about pilot-behaviour concerning the actual flight plan (Pilot Modelling, done by the module *Pilot Behaviour Interpreter*).

Expected crew actions are compared with the actual behaviour shown by the crew. If the actual pilot behaviour differs from the expected behaviour the module *Pilot Intent and Error Recognition* tries to figure out, if the deviation was caused erroneously. Detected errors are issued to the crew by warnings and hints which will help the pilot to correct slips. This is the normal, inner loop.

By monitoring pilot actions in the second loop as well as the mission context, the system is able to compare the pilot's actions to a set of behaviour hypotheses. In case of an intentional deviation from the flight plan, the module checks, if the behaviour fits to a given set of intent hypotheses. These hypotheses represent behaviour patterns of pilots, for example, when commencing a missed approach or avoid a thunderstorm.

With the intention recognized, support like re-planning is initiated.

Humans, however, often solve complex problems using very abstract, symbolic approaches which are not well suited for implementation in conventional languages. One of the results in the area of artificial intelligence has been the development of techniques which allow the modelling of information at higher levels of abstraction.

These techniques are embodied in languages and tools which allow to develop algorithms very similar to the human logic and to maintain large knowledge bases.

The supporting technologies for the systems function of monitoring the pilot behaviour will be briefly described behind each step of monitoring the pilot's behaviour.

#### a) Pilot Modelling

Modelling of pilot behaviour is done in two ways. The *normative model* describes deterministic pilot behaviour as documented in pilot handbooks and air traffic regulations. Modelling considers primarily the domain of rule-based behaviour. The *adaptive model* contains behavioural parameters of the individual pilot, when specifically differing from the normative model.

The analysis of pilot tasks in order to choose an adequate modelling formalism shows, that

- pilot tasks are *strongly concurrent* (e.g. maintaining altitude while reducing airspeed while communicating with ATC),
- processing of pilot tasks is driven by situation-dependent choices of different rule-domains (e.g. cruise navigation or approach navigation), this is a *choice between (excluding) alternatives*,
- the basic element within the considered task is always a *causal relation*, which can be formulated as production rule (if ... then),
- the situation space as well as the pilot's action space can be described by *discrete states* (e.g. flight segments, flaps settings) and *state transitions* (flight segment transition, flaps setting transition);
- State transitions are driven by *discrete events* ("passing station X, reaching altitude Y").

Concerning these characteristics, *Petri nets* were chosen as most a backbone for knowledge representation purposes [26].

In current research the normative behaviour model as described above is being enhanced by providing information on the individual parameters. The aim is to achieve a *customized* model output in order

- to improve model accuracy,
- to cover areas of behaviour not yet described in the normative model and as a result
- to improve pilot acceptance.

A hybrid petri net/ CBR system is in progress using methods of example based reasoning to overcome particular shortcomings. [27]

A more recent approach uses a database of previously experienced *cases* as a repository for reusable solutions. Each case comprises an onset state, a target state and individual intermediate states and state transitions. During this *example based reasoning* approach *case retrieval* (or *initially match*) isolates those cases in the case base, that are considered to be compatible to the actual task. Emphasis is given on fast retrieval speed.

#### b) Intent and Error Recognition

Current theories, which are dealing with the human error process, are defining errors as a not complying with the given goals, and assume errors should be avoidable. Talking about a human error means the actor has done something which:

- was not intended,
- was not allowed by a prescribed set of rules or an external observer or
- led the task or system outside its acceptable limits.

The basic types of errors could be distinguished between a planning failure (mistake) and an execution failure (slip). A mistake is something the actor intended but which will result in a conflict in the future. Thus, a mistake is an incorrect decision or choice, or an error in deciding what is to be intended. A slip is defined as an action not complying with the actor's intention. The corresponding plan might have been good, but the execution was poor. In order to detect a mistake or slip intent-recognition of the actor is required. Moreover, detection of mistakes requires prediction of future actions. Thus the notion of intent and error are closely related.

Intent recognition applies machine intelligence for deriving the goals and subordinate actions of the human operator in the context of a complex situation. Intent recognition can support man-machine synergy by anticipating need for machine assistance without waiting for requests by the operator. For it, a problem solving system must be able to provide an interpretation of each situation. This interpretation is based on a set of rules of inference. The rule-based approach is commonly used for developing systems, which models human behaviour in well defined problem domains.

However, in many real life applications areas such as aerospace, decisions have to be taken based on inexact or uncertain knowledge. If decision makers are to be supported by computer systems, it is desirable that this type of knowledge can be represented. To cope with the problem of reasoning under uncertainty several methods like Bayesian inference or Dempster-Shafer theory have been developed.

Another approach is the classification by use of fuzzy logic to represent diagnostic knowledge. [28]. This comprises to:

- the evidence of a feature with respect to an error or intent hypothesis and
- the logical role of some information in confirming or rejecting an error or intent hypothesis.

The advantages of this approach are:

- universality of representation: all types of uncertainty can be modelled
- correspondence with human situation description
- compliance with human reasoning
- ease of understanding/manipulation
- adequacy of representation: the information is accurately modelled
- computational efficiency.

### 3.3.4 CASSY and CAMA

Intelligent assistant systems have been developed at the University of the German Armed Forces, Munich together with industry partners. The Cockpit Assistant SYstem (CASSY) for commercial aircraft under instrument flight rules in the ground-controlled airspace has already been flight tested successfully. At the time being, the newest development CAMA (Crew Assistant Military Aircraft) for military transport aircraft has reached the integration phase in the flight simulator facility of the University.

#### 3.3.4.1 The Cockpit Assistant System CASSY

To comply with the discussed ideas a single, integrated avionic subsystem CASSY presents a possible solution for civil transport aircraft (Figure 3.3-3).

The **Automatic Flight Planner** module (AFP) generates a complete global flight plan [29]. On the basis of its knowledge of mission goal, ATC instructions, aircraft systems status and environmental data an optimized 3D/4D trajectory flight plan is calculated. The flight plan, or several plans, is presented as a proposal which the crew accepts or modifies. Once a flight plan is chosen it serves as a knowledge source for other CASSY modules. The AFP recognizes conflicts which may occur during the flight, e.g. due to changing environmental conditions or system failure, and appropriate replanning is initiated. If necessary, this replanning process includes the evaluation and

selection of alternate airports. Since the module has access to ATC instructions, radar vectors are incorporated in the flight plan autonomously and the system estimates the probable flight plan.

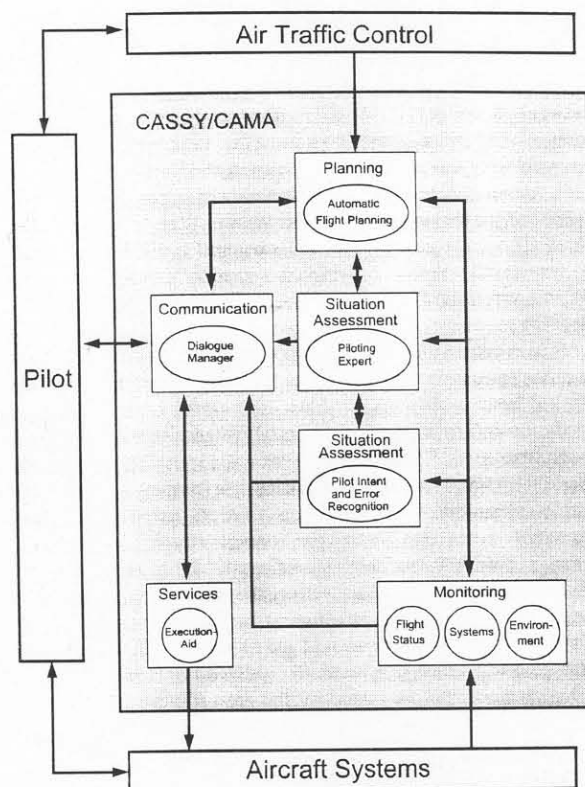


Figure 3.3-3 Core elements of the Cockpit Assistant System CASSY

The module **Piloting Expert** (PE) uses the valid flight plan to generate necessary crew actions. It is responsible for processing a crew behaviour model [26]. The normative model describes the deterministic pilot behaviour as it is published in pilot handbooks and air traffic regulations. The model refers to flight guidance procedures concerning altitude, speed, course and heading, but also to aircraft systems management. Given the flight plan and a pointer on the current leg, provided by the Monitoring of Flight Status, the system determines the appropriate normative values and tolerances on aircraft systems and flight status data.

In the module **Pilot Intent and Error Recognition** (PIER) [30] the expected crew actions are compared with the behaviour actually shown by the crew. The crew actions are derived indirectly by interpreting the aircraft data and pilot actions. If given tolerances from PE are violated, the crew will be informed by advice and warnings and detected mistakes are indicated to the pilots. In the case the crew deviates intentionally from the flight plan, the module checks if the behaviour fits to a given set of intent hypotheses which are also part of the crew model. These hypotheses represent behaviour patterns of pilots in certain cases, e.g. tasks to be done when commencing a missed approach procedure or to deviate from the flight plan to avoid a thunderstorm ahead. When an intentional flight plan deviation and the respective hypothesis is recognized, appropriate support, e.g. replanning is initiated.

Additional monitoring functions are needed to enable the system to recognize and interpret the current situation. The **Monitoring of Flight Status** provides the present flight state and progress. It is also able to report the achievements of the flight's sub-goals. The **Monitoring of Environment** gathers information of the surrounding traffic, e.g. from TCAS and of

weather conditions, also it incorporates a detailed navigational data base of the surrounding area. The health status of aircraft systems are monitored by the **Monitor of Systems** like a diagnosis system.

Communication plays an important role in CASSY. The kind of information to be transmitted in either direction varies with respect to the different modules. The information flow from CASSY to the crew and vice versa is controlled by the module **Dialogue Manager (DM)** [31]. The many different kinds of messages require a processing in order to use an appropriate display device and to present the message at the right time. As output devices both, a graphic/alphanumeric color display and speech synthesizer are used. Short warnings and hints are used to make the crew aware of a necessary and expected action and are transmitted verbally using the speech synthesizer. More complex information, e.g. the current flight plan, is depicted on a moving map on the graphic display.

Another important feature of the DM is that a priority ranking of the output message is evaluated and the most important message is issued first.

The input information flow is established by use of speech recognition in addition to conventional input mechanisms. In order to improve speech recognition performance, almost the complete knowledge of CASSY is used to provide situation-dependent syntaxes. Thus, the complexity of the overall language model is reduced significantly. The use of speech input and output devices also reflect the idea of human-centered development with respect to efficient communication.

In the module **Execution Aid (EA)** several functions like aircraft settings, navigation calculations and data base inquiries are realized and can be issued by the crew. These functions are similar to available automated functions in today's aircraft. For the pilots, the main difference is the use of speech input which facilitates the use of these services.

#### Results of the flight testing

After successful simulator tests, CASSY has undergone an eleven hours flight test program.

The modules of CASSY have been implemented in an off-the-shelf available Silicon Graphics Indigo workstation using the programming language C. A Marconi MR8 PC card was used as speaker-dependent, continuous speech recognition system. A DECTalk speech synthesizer served as speech output device using three different voices enabling the pilot to distinguish different levels of severity of messages. The components were connected using serial lines and ethernet.

The system was integrated into the test aircraft ATTAS (Advanced Technologies and Testing Aircraft) of the Deutsche Forschungsanstalt für Luft- und Raumfahrttechnik (DLR) in Braunschweig. The aircraft is well equipped for flight guidance experiments as it is possible to operate the aircraft via a single seat experimental cockpit located in the cabin. For testing typical IFR- scenarios, destinations such as the international airports Frankfurt, Hamburg and Hannover were chosen, starting from the home-base Braunschweig.

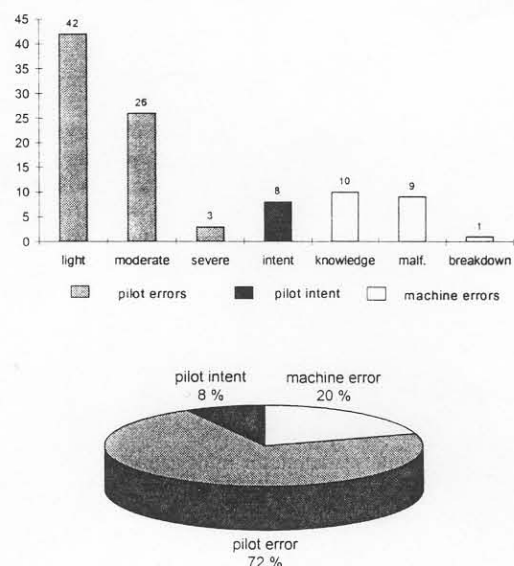
The experiments proved CASSY's functions throughout the complete flight from the take-off to landing. Speech recognition performed well in the aircraft as the surrounding noise was primarily engine noise which did not change much during flight. The recognition rates were similar to those achieved in the more quiet flight simulator environment at the University in Munich where CASSY was developed and tested prior to the flight test. One important aspect of the tests was to prove the system in the high density air traffic in the near terminal area of German airports. During the campaign, any given ATC instruction could be processed and integrated into the flight plan by CASSY.

Pilot Errors were detected and the appropriate warnings were issued. System errors on the side of CASSY were uncritical in any case.

A total amount of 100 incidents leading to warnings have been evaluated to find out the reasons for the warnings and messages of similar purpose and the consequences they had. All incidents

have been related to one of the three categories: pilot error, pilot intent and machine error (i.e. CASSY errors in this case) (**Figure 3.3-4**).

In five cases of the intentional deviations from the flight plan the intention was autonomously figured out by the assistant system and the flight plan has been adapted, accordingly. In three cases the pilot had to inform CASSY about his intention. Half of the machine errors were caused by an incomplete knowledge base, e.g. insufficient modelling of the aircraft performance and the other half by malfunctions of CASSY, i.e. software implementation errors due to less rigorous application of software development procedures. In one case such a malfunction led to a complete breakdown of the assistant system. In all machine error cases the pilot realized that a wrong warning was issued by CASSY. No negative influence on the pilot's situation assessment could be observed. In the one breakdown case, the complete CASSY system had to be restarted in flight, which took about 15 seconds. The only pilot input needed for such a recovery procedure is the flight destination. In all other machine error cases the warnings disappeared autonomously, when the incorrect assessed maneuver had been completed by the pilot.



**Figure 3.3-4 Error count during flight tests**

Concerning the pilot errors the light errors are considered to result in an inaccurate or uneconomical, but safe maneuver. Moderate errors, probably would lead to a safety critical situation, and severe errors surely would lead to a dangerous safety hazard unless an immediate correction is made. All pilot errors, which occurred during the flight tests, were detected by CASSY. All moderate and severe errors as well as about 70% of the light errors were immediately corrected by the pilot after having received the warning or hint.

This means there were no significant negative consequences of errors or failures whether caused by the pilot or by CASSY. This is the symbiotic effect which is wanted!

Two pilots were flying with CASSY in the test aircraft. Additional pilots from Lufthansa German Airlines were sitting aside to observe the tests and assess the system's performances. CASSY was well accepted by the pilots throughout the campaign. In particular, the pilots appreciated the autonomous flight plan function of CASSY. Warnings and hints were considered as justified and helpful. Speech input was generally used when complex inputs were to be made, e.g. frequency settings by using the name of the station instead of its frequency.

The experience with the Cockpit Assistant System CASSY in real IFR-flights have demonstrated this kind of system can cope with the real air traffic environment [32].

### 3.3.4.2 The Crew Assistant Military Aircraft CAMA

In future military transport aircraft, constraints created by low level flying in a high risk theater, the high rate of change of information and short reaction times will produce physiological and cognitive problems for the pilots. Low level flying over rapidly changing terrain elevation coupled with complex and dynamic tactical environment will result primarily in difficulties to maintain situation awareness.

With CAMA (*Crew Assistant Military Aircraft*) a novel approach breaks new ground to effectively enhance situation awareness in future military aircraft. This knowledge-based aiding system is being developed and tested in close cooperation between the DASA (Daimler-Benz Aerospace), DLR (German Aerospace Research Establishment), ESG (Elektronik- und Logistiksysteme GmbH) and the University of the German Armed Forces, Munich, based on the experience with CASSY. (Figure 3.3-5)

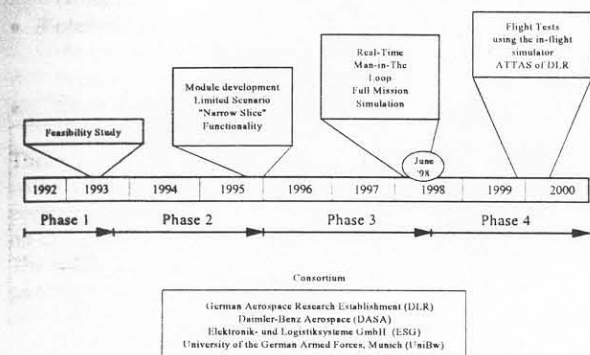


Figure 3.3-5 The CAMA Program

The CAMA-program was planned for four phases including a pre-contract feasibility study, a module development phase in a limited scenario for each module, and an integration phase with several testing steps. The actual integration phase will end in June 1998 with a man-in-the-loop full mission simulation campaign. After simulator tests the system will be demonstrated in flight experiments which are scheduled for winter 1999. It is planned, that CAMA will be integrated in the experimental cockpit of the ATTAS test aircraft of the German Aerospace Research Establishment (DLR).

CAMA assists the crew during a tactical mission to enhance situation awareness with an *interpretation of*:

- the altering tactical situation
- the actual weather situation
- the flight trajectory ahead to avoid safety critical ground proximity
- other safety relevant events

and through mission execution *services like*:

- an optimized 3D/4D trajectory flight plan
- time-management with regard to Time Over Targets (TOT)
- landing guidance without ground infrastructure
- evaluation and recommendation of alternates

Necessary *communication* with ground facilities like Command and Control Centers or Air Traffic Control (ATC) are provided by data link.

The overall *information flow* from CAMA to the crew and vice versa is controlled by the dialogue management.

As most important distinction from CASSY, CAMA takes the tactical situation into account.

The module **Tactical Situation Interpreter** (ESG) monitors tactical events and threat characteristics to analyze the transport

mission situation. Threat data are assessed based upon digital terrain and elevation data (DTED) as well as the threat's models. The algorithm allows to calculate a position-dependent threat value taking terrain masking against the opponents radar into account. An internal *threat map* contains a complete representation of the tactical situation including field fortifications, SAM emplacements, lines of troops, fighter threat, hostile and own AWACS etc. [33].

The **Flight Situation and Threat Interpreter** module (UniBw) combines stored mission data with current or proposed plans and the results of the situation interpretation modules. Its main contribution is to find any plan-conflicts and to initiate a conflict-solving process.

The **Mission Planner** (UniBw) creates and maintains a take-off-to-landing mission flight plan, including routes, profiles, time- and fuel-planning based on knowledge about the mission plan, gaming area, destination, ATC instruction, aircraft status, environmental data, etc.. Events like failures of aircraft systems, weather or threat changes and ATC or C&C instruction and information are taken into consideration. The mission planner covers the flight under Instrument Flight Rules (IFR) as well as tactical routing. Time management, especially with regard to a TOT (time over target), fuel calculations and routes/profiles calculations will assist the crew. The calculated trajectory is presented as proposal to be accepted or modified and serves as knowledge source for other function blocks.

The **Low Altitude Planner** (ESG) calculates the trajectory based on knowledge about weapon and system capabilities. Minimum risk routes are chosen to bypass hostile defenses.

Based on the aforementioned *threat map* the LAP generates an optimized low level flight plan by calculation of a minimum risk route through the gaming area. In generating plans, account is taken to the current situation and available resources, such as fuel or time, while complying with waypoint restrictions and other mission constraints [33].

The module **Terrain Interpreter** (DASA) contains a digital terrain data base to warn the cockpit crew if the projected aircraft path is getting too close to the ground or an obstacle. This eliminates several traps such as controlled flight into terrain or descend into ground short of the runway.

The aircraft may need to be updated with fresh information during the mission. The **External Communication Interface** (DASA) will provide the crew and assistant system with external data, like weather forecasts, the intention of external war-fighting units or changed tactical situations that might effect the planned mission.

The module **System Interpreter** (DLR) monitors and analyses on-board systems to determine the current state of the aircraft systems. Any detected malfunction is evaluated to determine the degree of degradation of the overall system capability.

The module **Computer Vision External** (UniBw) will assist the crew by computer vision during the approach phase to avoid collisions in high density air traffic and to ensure a quasi ILS/MLS landing at any unequipped landing field. To improve the aircraft state estimation, a camera-system will be used to determine the relative position to the runway. Two cameras with different focal lengths are used in parallel for bifocal vision. A wide-angle lens is used for initialization and stabilization and the tele-lens for object tracking. The system has been tested in real-time with a hardware-in-the-loop simulation. Image processing combined with the current inertial sensors are able to perform precise landing guidance. [34]

To improve the reasoning capability pilot model, the eye movement of the pilots will be evaluated. With the module **Computer Vision Internal** (UniBw) a camera system similar to the hardware configuration of the module Computer Vision External is used to register head and eye movements of the aircrew. This information, for instance the moving line of sight to a control surface or to a special indicator, could be used to confirm the need for a warning or a hint. The measurement is remote.

The **Pilot Behavior Reference** (UniBw) module describes a rule-based model of expected pilot-behavior concerning the actual flight plan and the module **Pilot Intent and Error Recognition** (UniBw) evaluates the pilot's activities and mission events in order to interpret and understand the pilot's actions like presented in chapter 4.

The information flow from the machine to the crew and vice versa is controlled exclusively by the module **Dialogue Manager** (UniBw) [31] which corresponds to the CASSY dialogue-management (see above) [31]. A substantial innovation is a Horizontal Situation Display. The Horizontal Situation Display is an interactive touch-sensitive map display organised in a number of layers which allows the crew to optionally select from several map-presentations in any combination. It allows to depict tactical and threat information as well as a variety of navigational elements and a topographical map similar to the currently used low flying charts paper-maps. A second alpha-numerical display contains the flight-log and is used for in-flight departure-, approach- or missed-approach-briefings.

### 3.4 Computer Oriented Metering Planning and Advisory System (COMPAS)

#### 3.4.1 Overview<sup>1</sup>

The objective of Air Traffic Control/Air Traffic Management is to ensure safe, efficient and timely operations of a large number of aircraft using the same airspace at the same time. A pilot of an individual aircraft generally has very little knowledge about and no control of the other traffic. Consequently an independent, ground-based authority, i.e. Air Traffic Control (ATC), has been established to coordinate and control all traffic operations in a given air space.

Air traffic control can be considered as a work system where human operators make use of a variety of ground-based and on-board sensor systems to collect information. Similarly, they use different ground-based and, largely through the pilot on-board, effector systems to implement their intentions and commands. However, most, if not all, processing functions are currently still carried out in the brains of human controllers. In many high density traffic areas the human control capacity has already become the limiting factor in the overall system performance of the ATC system. In order to cope with future increased air traffic demand and to overcome the limitations of the human information processing capabilities, more and more of the information processing functions of the human ATC controllers must be supported by or even replaced by intelligent machine functions.

The COMPAS system [35-40] which is described in this section is an example of the successful introduction of knowledge-based planning support in air traffic control. COMPAS is a planning tool to assist the controller in the handling of arrival flights in the extended terminal area of major airports. It aims at improving the flow of traffic and the efficient use of the available airport landing capacity while reducing planning and coordination effort of ATC personnel. The system has reduced controller workload of the approach controller team and does not cause any significant additional load to the en-route controller teams.

Main basic functions of the system are monitoring and diagnosis of the traffic situation based upon the on-line input of the initial flight plans, actual radar data and the actual wind. Basic planning parameters such as: aircraft performance data, airspace structure, approach procedures and controller strategies, separation standards and wind models are already stored in the computer and do not require additional inputs by the controller.

Each time a new aircraft enters the predefined planning area, COMPAS determines the optimal sequence of all approaching aircraft and calculates a schedule of arrival times for the "Metering Fix", a waypoint at the Terminal Maneuvering Area (TMA) boundary and the "Approach Gate", a waypoint on the runway centerline. The computer-derived optimum sequence and schedule and some advisories on achieving the desired plan are displayed to all controller teams who are responsible for the control of the inbound traffic. Each of these teams receives only those data which are necessary to control the arriving flights in its sector and to contribute to the optimized overall plan. Usually there is no interaction required between COMPAS and the human operator. However, the controller has the ability, if he sees the need, to modify the computer generated plan or to change planning parameters and constraints through a small function keyboard.

#### 3.4.2 Arrival Planning at Airports

The generic, top-level functional structure introduced in section 2.3 can be applied to *arrival sequencing and scheduling* as illustrated in Figure 3.4-1.

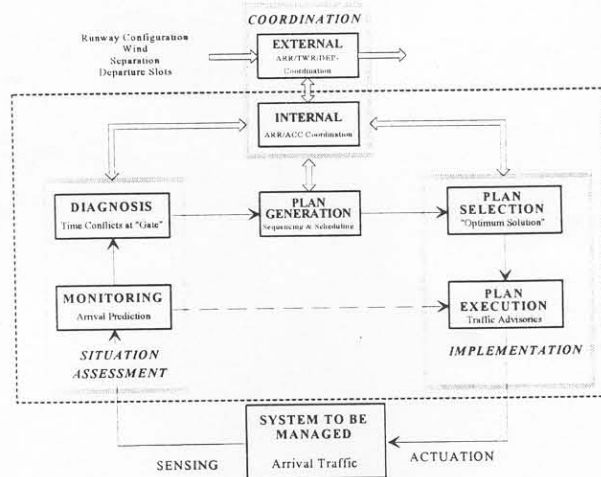


Figure 3.4-1 Generic Structure of Arrival Sequencing and Scheduling Functions

Figure 3.4-1 illustrates the arrival sequencing and scheduling functions as part of the short-term-planning layer of ATM/ATC. At this level, the system-to be controlled is the actual air traffic, a set of inbound aircraft. Their flight plans, positions, altitudes and identifications are continuously sent from different sensor systems to the situation assessment function. Here, headings, tracks, speeds, descent profiles etc. are continuously calculated and sent to the diagnosis function. The diagnosis function predicts, extrapolates and correlates future trajectories to detect deviations from the plan and to detect potential future conflicts. If a planning conflict has been found, the plan generation function is activated. It attempts to resolve the conflict by using stored solutions or stored problem solving methods. The plan generation results represent tentative solutions for the sequence, schedule and trajectories for the inbound flights. These planned and still tentative solutions must be coordinated with other planning agents (e.g., adjacent upstream ATC-sectors, the downstream tower sector, with departure control). After an agreement has been reached through coordination, the potential solutions are transferred for implementation. Here they are evaluated and the "best" solution with respect to a given goal criterion is selected. The solution is executed by the plan execution function which transforms the solution (sequence, schedule, trajectory) into commands (heading, speed, descent, intercept etc.) which are transmitted to the systems-to-be-controlled: the arriving aircraft.

<sup>1</sup> The presentation in the section 3.4 follows the description of COMPAS in [7]

Some of these functions can have the potential for being implemented by an intelligent computerized planning system to support the human operator in the control of arrival traffic. In COMPAS, the monitoring, diagnosis, and planning functions are performed automatically and continuously by the computer. The results, the *COMPAS plan*, are presented through a specially designed Human-Computer-Interface (HMI) to the human operator. The human controller can integrate the COMPAS generated plan into his other control activities and retains the ultimate authority for decision making and implementation. He is also able to interact with the computerized planning function through the HMI.

### 3.4.3 Monitoring, Diagnosis and Planning Functions

The whole process is divided into several steps:

- the acquisition and extraction of radar and flight plan data (**Monitoring**)
- the prediction of the flight profile and the calculation of the arrival times (ETO) as if the aircraft were alone in the system, checking for time-conflicts at the so-called "Gate" (**Diagnosis**)
- planning of the optimal overall sequence and calculation of the planned arrival times with minimum total delay for all known inbound flights (**Planning**)
- freezing of the planning status when the aircraft reaches its top of descent.

There are several assumptions within the flight profile model with regard to an economical descent profile and the performance of the type of aircraft. A simplified method based on airline operations data was developed for profile prediction. The different profile legs are calculated with the actual radar position, airspeed, flight plan data, altitude, wind data as received on-line from the ATC data processing system. Further consideration is given to the aircraft type-specific economical descent gradient, minimum cost descent speed, the aircraft deceleration rate and possible air traffic constraints at the Metering Fix and the Approach Gate. The estimated time of arrival (ETO) is based on the preferential flight profile of the aircraft. The earliest estimated time of arrival (EETO) takes into account all measures to advance the aircraft within its performance envelope without requiring any thrust increase. The time difference between ETO and EETO is used as a margin for sequence changes to maximize traffic throughput without violating economical flight conditions.

With its EETO, the newly entering aircraft is inserted into the already existing sequence (see **Figure 3.4-2**). The result is an initial plan, i.e., a tentative sequence of aircraft according to the 'first-come-first-served' principle, but possibly with still unresolved time-conflicts.

As an example of the knowledge-based core functions in COMPAS, the planning algorithm to establish the optimal sequence and schedule shall be described briefly. It is an analytical 'Branch-and-Bound' algorithm with three major elements.

- merging of new arrivals into the sequence
- time conflict detection and
- time conflict resolution with optimization criteria.

The overall goal here is to minimize the total delay time by optimal combination of the aircraft of different weight classes. A dense sequence of aircraft (i.e., minimum total delay) contributes to the best utilization of the available runway capacity. The algorithm can be graphically represented as a heuristically oriented search in a decision tree. The nodes represent the individual sequence pairs which are characterized by the earliest time conflict between two aircraft in each case.

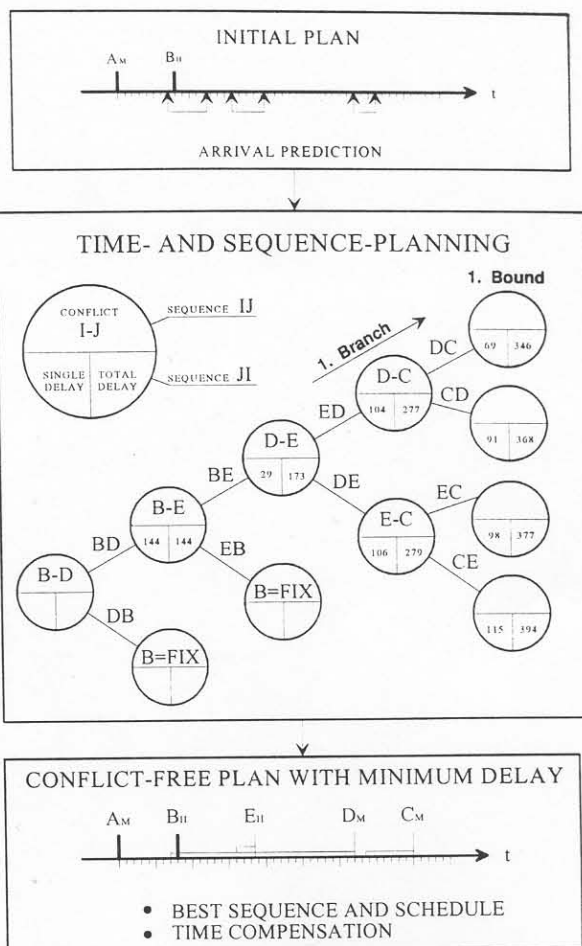


Figure 3.4-2 COMPAS Planning Algorithm

The branches show the alternatives for conflict resolution and the decision tree is developed following the principle 'solve-the-earliest-conflict-first'. The cost function is the total delay time, which is accumulated until a conflict free plan is found. The cost value of this first solution is called 'first bound' (usually it is a sub-optimal sequence). A backtracking procedure leads sequentially to all those nodes with less than the total delay of the first bound. From there new branches in the search tree are developed. The development of a new branch will be stopped either when the total delay value of the 'first bound' is exceeded or it leads to a new bound with less total delay. The planning process ends when all remaining conflicts have been resolved. The result is a sequence for all known inbound flights with the shortest time separation between any preceding and trailing aircraft equal or greater than minimum permitted separation and a planned delivery time for all arrivals at the so-called "approach gate". From this "gate time" all other intermediate arrival times for other waypoints are calculated individually for each actual flight. Furthermore, an advisory is calculated which defines how much each arrival has to be advanced or delayed.

### 3.4.4 Man-Machine Interaction

The layout of the man-machine interface of COMPAS was of crucial importance to the acceptance of the whole planning system. "Keep the controller in the loop". "Give him the plan, but leave the implementation to his experience, skill and flexibility". "Minimize the need for keyboard entries and keep the advisories as simple as possible". These were the main guidelines and principles for the design of the Human-Computer interface, i.e. the COMPAS-display and the COMPAS-keyboard.

Figure 3.4-3 shows the cooperation between human and computer-based functions for the COMPAS system.

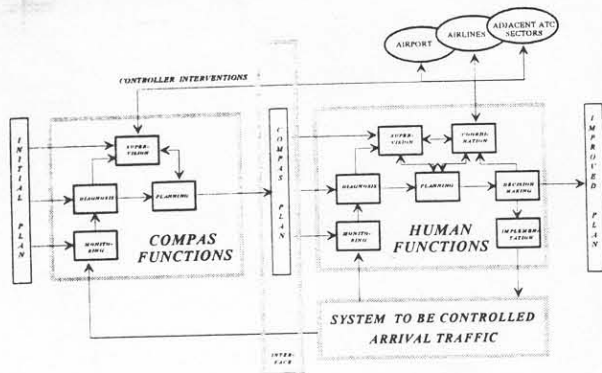


Figure 3.4-3 Man-Machine Interactions in COMPAS

#### 3.4.4.1 Display

The display of the solutions from sequencing and scheduling is specially tailored to the needs of the different ATC units (Enroute and Approach) which are involved in the handling of inbound traffic. Figure 3.4-4 shows the features of the controller display. The planned aircraft in the arrival flow are listed sequentially in a vertical time line, with the earliest arrival at the bottom. The aircraft labels are additionally marked with 'H' or 'L' according to the weight categories of the individual aircraft (H=HEAVY, L=LIGHT, the standard MEDIUM category is not indicated explicitly). The vertical position of each arrival is correlated with a vertical time line which moves downward with the progress of time. The bottom of the line represents the planned time over the Metering Fix (enroute display) or Approach Gate (approach display). A color code is used to indicate from which approach sector the aircraft are coming. The letters left of the time line give a rough indication (advisory) of the suggested control action for each aircraft during the descent phase. Four characters are defined in order to reach the planned arrival time and to establish a dense, smooth traffic flow ('X' = an acceleration of up to two minutes, 'O' = no action, 'R' = a delay of up to four minutes and 'H' = more than four minutes delay). The controller is free to accept or to reject the advisory. He can modify the computer-generated sequencing plan if he desires or if unforeseen events have occurred. In addition the display shows, at top right, two basic parameters for information: the active runway direction (e.g. 25) and the so-called "FLOW", which actually tells the minimum permitted and planned separation.

The controller can move a cursor up or down on the time line to identify a specific aircraft or time window if he wants to enter modifications.

#### 3.4.4.2 Keyboard

Figure 3.4-5 shows the intentionally very simple functional keyboard for controller-computer interaction. There are ten function keys to change the basic parameters or operational functions.

Inputs to modify the basic planning parameters can only be entered by the approach controller, i.e.:

- change of minimum separation (FLOW),
- change of landing direction (RWY CHG) and
- STOP in case of closure of runways.

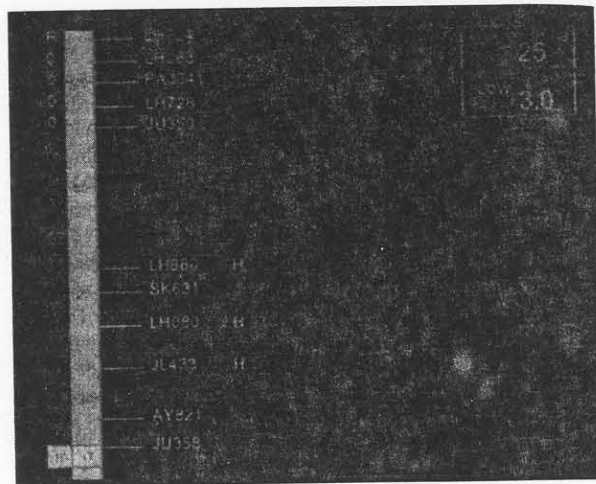


Figure 3.4-4 COMPAS Enroute Controller Display

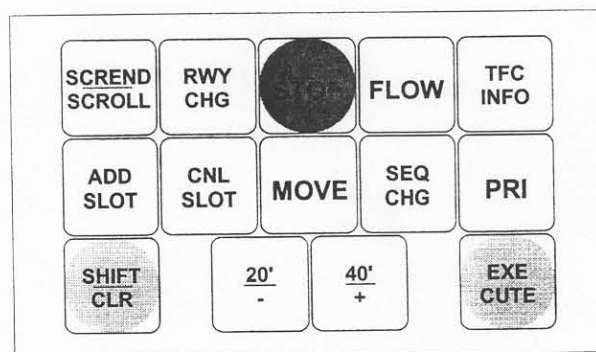


Figure 3.4-5 COMPAS Keyboard

Inputs to modify the automatically generated sequence and schedule can be entered at all controller keyboards, both in the enroute and approach sectors, i.e.:

- insertion of arrivals unknown to the system into sequence (ADD SLOT),
- cancellation of planned arrivals (CNL SLOT),
- move an arrival over several positions in the sequence (MOVE),
- change of planned sequence between two successive aircraft (SEQ CHG),
- assign priority to an arrival (e.g. emergency, ambulance, etc.) (PRI)
- display of additional information to the en-route controller (TFC INFO), to give additional information about aircraft in adjacent sectors.

#### 3.4.5 Successful Implementation of COMPAS at Frankfurt Airport

The COMPAS-system was installed in the Frankfurt/Main Air Traffic Control Center of DFS, the German Air Traffic Services in 1989. Since then it has been used successfully, 24-hours-a-day, and has shown improved traffic flow and throughput. It has found overwhelming acceptance with the human operators. As scientific, statistically proven studies have shown, this is mainly due to the planning results which are generated by the knowledge-based functions. They are reasonable, feasible and easy to comprehend and to apply. Controllers feel that these advisories are "non-intrusive", and give an easy-to-follow framework plan while allowing them to stay in the loop with some flexibility to make changes. Above all, the controllers

remain the ultimate authority and responsibility. Results of the field evaluations can be found in Reference [40].

The present development of COMPAS is focused on two main directions:

- Incorporation of more sophisticated models, advanced planning technologies and heuristic planning methods.
- Full integration with other planning support tools for ATC Terminal Automation, (e.g.: 4D-Planning; Wake Vortex Warning System; Arrival/Departure Coordination; Airport Surface Traffic Management).

This will be achieved through the application of advanced knowledge-based technologies (e.g.: Multi-Agent Planning; Hierarchical Planning; Multi Sensor Data Fusion; Information Management).

## 4 COMPLEX AND DISTRIBUTED DECISION MAKING

In the chapter 3 several examples of intelligent decision aids for human operators have been discussed. APES, Copilot Electronique, CASSY and CAMA are systems which support the functions of a pilot in the cockpit of military or civilian aircraft (see Figures 3.1-1, 3.2-3 and 3.3-3). They can be considered as work systems (see Figure 2.2-1) where the decision aid has the role of the *tool*, and the aircraft is the *work object*.

In the case of COMPAS the situation is more complex: This system supports more than 10 different air traffic controller working positions, each of which controls a different part of the airspace around an airport. (The Figure 3.4-3 shows the lay-out for only one working position.) The decision making process is distributed in this case among the various controllers and the COMPAS system in a cooperative workshare. This raises the question, how the *functional architecture* of such complex and distributed decision making systems can be modelled.

### 4.1 Networks of Coupled Work Systems

In chapter 2 the functional architecture of work systems which are managing aerospace systems was described (Figure 2.3-1). The coordination function of this architecture provides the possibility of coupling different work systems with each other (see also [7]). In this chapter, networks of coupled work systems will be used to model complex and distributed management processes, like air traffic management and command and control. Figure 4.1-1 shows the principle.

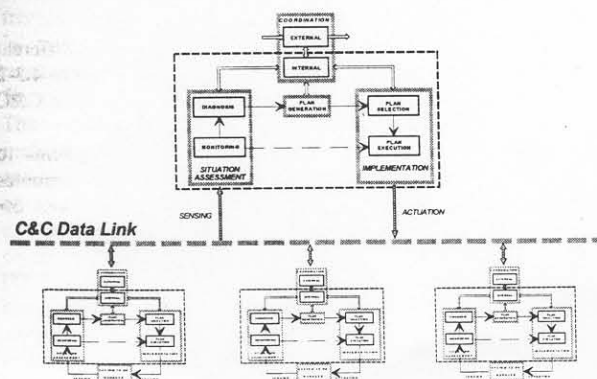


Figure 4.1-1 Hierarchical System of Coupled Work Processes

In this Figure four work systems are coupled through a data link. The three lower ones are using the data link for the *coordination* of their management functions. Each of them is dedicated to the management of a particular „system“. The coordination can be organised in different forms: Exchange of data (e.g. the plans), negotiations about the plans, setting constraints for the planning processes of the other work systems,

etc. The upper work system is „managing“ the three lower ones, employing its sensing and actuation functions. This principle of coupling is called *hierarchical*.

The principle of coupled work systems will be illustrated by some examples in the following sections.

### 4.2 Air Traffic Management (ATM)

#### 4.2.1 Distributed Decision Making in ATM

Air Traffic Management (ATM) is a good example for complex and distributed decision making:

- ATM is a very large scale system in terms of both time and space. The temporal scope is from long-term to the very immediate short-term. The spatial scope is from global to local. A broad variety of functions of different detail and character must be carried out in parallel at different levels, distributed over different time horizons and at different locations. Still, all information processing is interrelated and has to be coupled in numerous control loops.
- Most of the planning and control functions in ATM are highly complex. Many different requirements and constraints originating from airport operators, from airline operators, from pilots and from the environment (noise, pollution avoidance), which very often have competing or even contradicting goals, must be considered simultaneously. Some functions must be performed cooperatively between on-board and ground-based systems. Other ground-based functions and tasks are divided and allocated or shared among several different ground units.
- Despite of the application of the most advanced sensor technologies and data processing capabilities in ATM, it remains a significant challenge for planning and control functions to adapt continuously to changing conditions, i.e., to close all loops in real time. As ATM is, in principle, largely a customer service system, it must comply with airline, pilot, passenger, and airport needs. Unforeseen events, disturbances, and changing priorities are commonplace and occur on short-notice. Weather (headwinds, fog, thunderstorms, etc.) frequently add to the problems of uncertainty in ATM-planning and control.
- It is unlikely that in the foreseeable future there will be aircraft flying automatically without a pilot on-board, in airspace being automatically controlled without controllers on the ground. Thus, there will still be pilots and controllers in charge and responsible for the conduct of air traffic. Human limits in perception and information processing and the typical human approaches to planning and decision making (heuristic, holistic) all impose severe challenges on the designers of planning and decision support systems, who must model and transfer human cognitive processes to intelligent machines. Only when both the representation of information and the manner of dialogue and interaction with an intelligent device are acceptable to the human operator, will knowledge-based functions be successfully implemented, no matter how intelligent and advanced they may be.

#### 4.2.2 Functional Decomposition of ATM

Advanced operational concepts for ATM are presently under development in the USA (AAS [41]) and in Europe (EATMS [42]; CATMAC [43]). They follow a well designed, consistent architecture in which all ATM functions are deliberately coupled and performed by several autonomous, but cooperating planning agents. For example, in the german CATMAC (Cooperative Air Traffic Management Concept) proposal, the functions are decomposed:

- (1) In terms of time:
  - > strategic/long-term
  - > tactical/medium-term
  - > short-term planning
  - > actual control
- (2) In terms of space:
  - > global

- > continental
- > regional
- > local.

The ATM functions range from the very broad, high level strategic planning functions many months in advance of an actual flight, down to the very specific sub-tasks, e.g., resolving within seconds short term conflicts between two aircraft. In [44] the generic structure of the future ATM system has been discussed and is shown in the Figure 4.2-1.

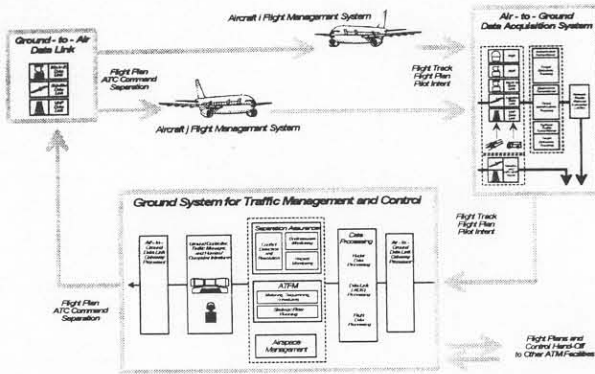


Figure 4.2-1 Generic Structure of the Air Traffic Management Function

This Figure illustrates the complexity of the functions needed to guarantee the safe and efficient flight of aircraft in a piece of airspace. The ground-based system for traffic management and control shows the infrastructure necessary to carry out the functions of separation assurance, air traffic flow management (ATFM) and airspace management. The ground-based system communicates with the on-board flight management system through a ground-to-air data link and an air-to-ground data acquisition system, using the same data link. The overall system can be considered as a network of coupled control loops with different time constants. Separation assurance has a time constant in the order of minutes or hours, ATFM in the order of hours or days, and airspace management in the order of days or even years.

The ground system in the Figure 4.2-1 serves a certain airspace. The functions of separation assurance, ATFM and airspace management have to be provided also in the adjacent airspaces. For this purpose the ground systems are coupled through data buses and voice communication systems. This creates a network of ground systems, which can be modelled as a system of coupled work systems. This principle will be explained with the example of COMPAS.

#### 4.2.3 Example: Distributed Planning in COMPAS

The COMPAS system has been described in the chapter 3.4. It provides an optimal plan for the sequencing and scheduling of all aircraft arriving at the airport of Frankfurt. The airspace which is used by these aircraft is controlled by more than 10 different controller working positions. The COMPAS plan is transmitted through a data bus to each of these positions, providing the controllers with those segments of the plan which corresponds to their airspace. The controllers can interact with the planning process using the COMPAS keyboard. This is shown schematically in the Figure 4.2-2.

This Figure describes a network of individual work systems (for the Sectors 1, 2 and 3), which are coupled through a common plan for the sequencing and scheduling of the aircraft under the control of these work systems. In this Figure the COMPAS system can be regarded as a fully automatic work system, which cooperates with the individual air traffic controller working positions (coordination in a hierarchical system).

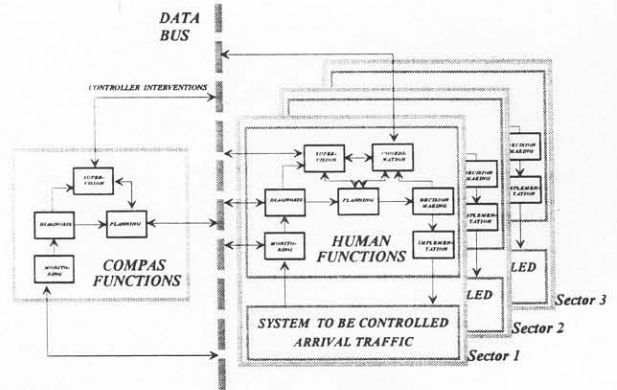


Figure 4.2-2 COMPAS as a System of Coupled Work Processes

### 4.3 Command and Control (C&C)

#### 4.3.1 Functional Decomposition of C&C

The structure of C&C processes is the subject of many research projects and studies (see e.g. [45]). The generic structure of a command and control loop is described in Figure 4.3-1.

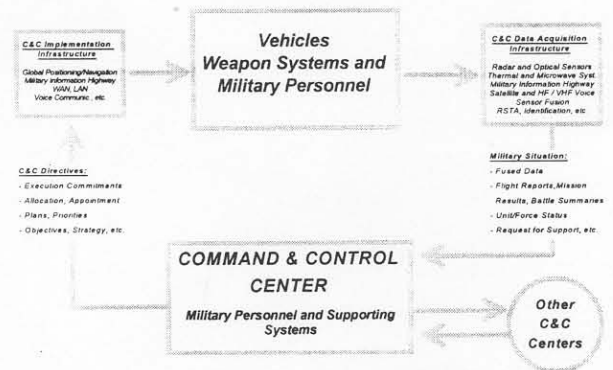


Figure 4.3-1 Generic Structure of the Command and Control Function

In a complex combat scenario, this loop exists for different command levels and temporal horizons (see [46]). Figure 4.3-2 shows the order of magnitude of the time constants of the C&C loops on the unit, force, component and theater levels.

The application of the concept of coupled work systems to command and control loops will be illustrated by the examples of distributed mission planning for military aircraft and air operations. These examples are discussed in more detail in [7].

### COMMAND & CONTROL LOOPS

Unit or Weapon System Level	(< 1 h)
Force Level	(< 4 h)
Component Level	(< 24 h)
Theater/Joint Force Level	(< 48 h)

Figure 4.3-2 Time Constants of the Command and Control Loops

### 4.3.2 Example: Distributed Mission Planning for Aircraft

For the on-board planning problem of a highly automated (potentially autonomous) air vehicle, mission and trajectory plans are developed within the military hierarchy to optimize an established objective function (e.g., minimize fuel, minimize time or maximize a mission-specific measure of accomplishment) subject to specified constraints (e.g., allocations on mission timelines, fuel, flight safety, etc.). A typical hierarchical decomposition of the mission planning problem is one wherein skeletal plans of the entire mission are constructed at the highest level, the *mission level*. The skeletal mission level plan must be generated in sufficient detail to ensure that on-board resources are sufficient to achieve the planned objectives and that timeline and survivability constraints are honored. At intermediate levels, the *route/activity levels*, near-term actions that are consistent with the mission level plan are planned in greater detail. Finally, at the lowest level of the hierarchy, the *flight safety level*, very near term commands are generated for sensor and control systems in a manner that ensures flight safety.

Figure 4.2-3 in the section 4.1 can be regarded as a two level decomposition of such a planning problem for three military aircraft (e.g. Unmanned Tactical Aircraft) which operate in the same airspace at the same time. The work system in the upper level creates skeletal mission plans spanning the entire mission of all three aircraft, and the 3 work systems in the lower level fill in the details of trajectory and payload activities that are required in the near term in pursuit of the mission plan of each individual aircraft.

The network of coupled work systems in the Figure 4.2-3 can be layed out as a *command system*, where the upper work system imposes mission plans to the individual aircraft; or as a *cooperative system* (distributed hierarchical and coordinated decision making); or as a mixture of both features, by the appropriate layout of the coordination function of the work systems.

### 4.3.3 Example: Functional Model of Air Operations

Military air operations are essentially plan oriented. At all levels from commander to combatant and in all domains, planning is the fundamental organizing principle and is the key to solving problems in combat. Thus, a planning paradigm is a "natural" representation of the full scope of military air operations. Such a paradigm is adopted here to provide a framework for a discussion of command and control functions in military air operations and to illustrate functional relationships between military air operations at levels ranging from theater to battlefield to individual missions.

The military notion of a "plan" evolves from a process that includes: (1) situation analysis; (2) determination of objectives; and, (3) selection of a course of action intended to realize the objectives. The process is viewed as iterative along a temporal axis and recursive at finer levels of detail across the hierarchical command. Thus, the generation of a plan at the highest level ("campaign") invokes the formulation of subordinate plans through a similar process at lower levels, in order to meet goals implicit in the planned courses of campaign level action. For example at the campaign level, a course of action is selected that calls for the defeat of enemy fielded forces. This course of action implies an objective to gain air superiority over enemy territory. That objective then generates a course of action indicating a sequence of combat actions against enemy air defenses. The objectives of these actions then define aircraft missions in the daily battle plan. Mission objectives finally result in the selection of targets for individual aircraft and mission plans are then crafted to create a desired effect on the targets. Thus, consistency of objectives across levels and coordination at every level in the command structure is effected, largely through the inheritance of plan objectives. The intermediate levels in the command hierarchy exist primarily to

provide insight at the appropriate scope into important operational detail.

From this perspective, military air operations may be conveniently mapped onto the functional model of coupled work systems developed in this chapter. Figure 4.3-3 shows this example.

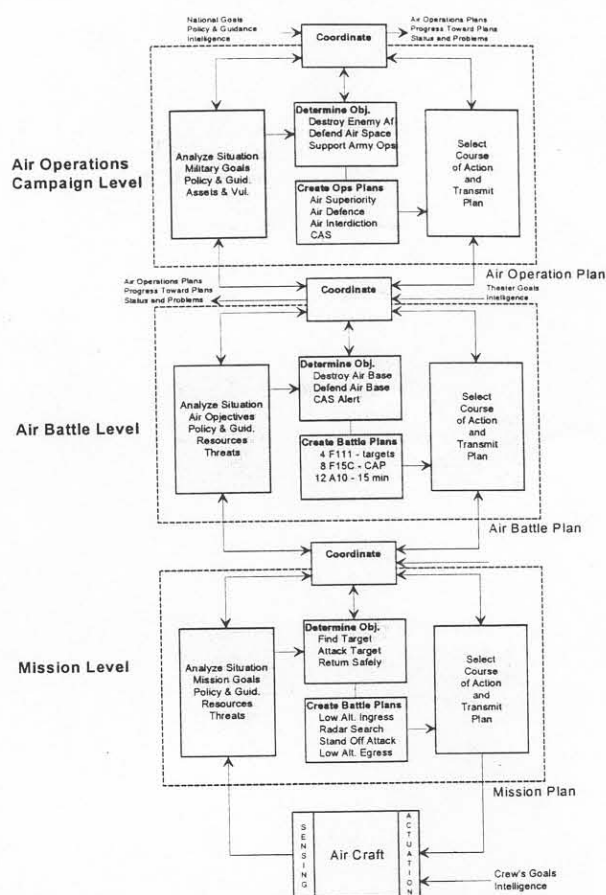


Figure 4.3-3 Functional Model of Air Operations

Thus, if we examine the model at the Senior Officer's level, the system under control is the command and control system for the theater. At a command center level, the system under control is the collection of assets that constitutes the force committed to battle. For combatants, the system to be controlled then, is the aircraft or weapons system at their command.

## 5 CONCLUSION

A functional analysis of human decision making has shown, that the concept of work systems is very helpful for the understanding and modelling of man-machine interactions in management tasks. Several successful examples of decision aids which have been developed in the USA, in France and in Germany were discussed in detail. They illustrate the design, development and evaluation of intelligent decision aids for the support of human operators.

In several of these examples, the decision process was concentrated upon one work system, the cockpit of an aircraft. In more complex functions, like air traffic management or command and control, the decision making process can be distributed in space and in time, so that several decision makers are taking part in the decision, at different times and/or locations. The concept of coupled work systems can be used to model these distributed decision making processes. Several examples were discussed to explain, how the principle of coupling elementary work systems can be applied to the design

of intelligent decision aids in such cases. The appropriate layout of the coupling mechanism allows the representation of command as well as cooperative structures.

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## **Future Aerospace Technology in the Service of the Alliance**

(les Technologies aéronautiques et spatiales du futur  
au service de l'Alliance atlantique)

**Volume 2:****Mission Systems Technologies**

(les Technologies des systèmes de conduite de mission)

*Unclassified papers presented at the AGARD Symposium held at the Ecole Polytechnique,  
Palaiseau, France, 14-17 April 1997.*

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<b>14. Abstract</b> <p>One of three volumes containing the unclassified papers presented at a conference on "Future Aerospace Technology in the Service of the Alliance" organised by AGARD (NATO's Advisory Group for Aerospace Research and Development) at Palaiseau, near Paris, France, 14-17 April 1997. The conference took the form of three parallel symposia and three plenary sessions.</p> <p>This volume contains the papers from the symposium on "Mission Systems Technologies", which had sessions on:</p> <ul style="list-style-type: none"> <li>• Mission Management Concepts</li> <li>• Sensors and Electronic Warfare</li> <li>• Information and Communication Systems</li> <li>• Information Fusion and Mission Systems Integration</li> <li>• System Simulation</li> </ul> <p>Volume 1 contains the papers from the three plenary sessions: "Future Directions in Aerospace Systems", "Future NATO Trends and Mission Scenarios", and "Human Machine Interaction in the Future"; and the papers on "Affordable Combat Aircraft".</p> <p>Volume 3 contains the papers on "Sustained Hypersonic Flight".</p>						